Applied Energy 168 (2016) 473–481

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Interactions of rooftop PV deployment with the capacity expansion of the bulk power system

Wesley Cole *, Haley Lewis, Ben Sigrin, Robert Margolis

Strategic Energy Analysis Center, National Renewable Energy Laboratory, Golden, CO 80401, United States

HIGHLIGHTS

- Novel linking of a capacity expansion model with a rooftop PV adoption model.
- Rooftop PV and utility PV generation have a nearly 1:1 substitution effect.
- Incorporating rooftop PV curtailments strongly impacts future rooftop PV adoption.

ARTICLE INFO

Article history:
Received 5 November 2015
Received in revised form 30 January 2016
Accepted 1 February 2016
Available online 13 February 2016

Keywords:
Rooftop PV adoption
Capacity expansion modeling
Grid integration
ReEDS
dSolar

ABSTRACT

Distribution-sited solar photovoltaics (PV) economics (including rooftop PV) have improved significantly during the past several years, spurring increased installations, with over 2.2 GW installed in 2014 in the United States. This increased deployment is largely projected to continue and has prompted additional interest in the interactions of rooftop PV deployment with the greater electricity system. In this paper we focus on one piece of this interface, namely the interaction between rooftop PV deployment and the evolution of the bulk power system. We develop a novel linkage between NREL's bulk power capacity expansion model (the Renewable Energy Deployment System [ReEDS] model) and NREL's rooftop PV adoption model (the dSolar model). We use these linked models to gain insights into the interactions of rooftop PV deployment with the bulk power system. We explore two sets of scenarios. In the first set we examine how different levels of rooftop PV deployment impact the generation mix on the bulk power system. In the second set we examine how the generation mix of the bulk power system impacts the deployment of rooftop PV by applying grid-wide curtailment rates to rooftop PV systems. In these sets of scenarios, we find that rooftop PV generation and utility PV generation have a nearly 1:1 substitution effect. We also find that curtailment rate feedback can have dramatic impacts on rooftop PV adoption, though the range of impacts is strongly dependent on the generation mix of the bulk power system and the amount of total PV generation in the system. For example, scenarios with more natural gas generation tended to have lower curtailment rates and thus more rooftop PV deployment.

1. Introduction

Economics of distribution-sited solar photovoltaics (PV) have improved rapidly, with installed prices declining more than 50% between 2010 and 2014, and installations in 2014 reaching 2.2 GW [1]. Adoption of PV is increasingly a financially attractive decision for broader sections of residential and commercial customers. However, there are important implications of increased levels of distributed PV generation. Large-scale adoption of rooftop PV may result in revenue loss for utility companies and may require additional investments in transmission and distribution infrastructure to accommodate the higher penetrations of this variable generation source [2–4]. In addition, increased levels of distributed generation will potentially reduce demand for competing generating resources, including natural gas, coal, and other renewable technologies such as utility-scale solar or land-based wind [5]. There are also unresolved issues with respect to defining the proper role of utility involvement in the diffusion of rooftop solar [6,7]. These considerations, coupled with the continuing decline of PV prices and associated increase in installations (see Fig. 1), highlight the importance of understanding the interactions of deployment of rooftop PV and the U.S. electricity system.

Traditionally, capacity planning exercises have given less attention to the contribution from utility-scale sources of variable generation, or have used broad assumptions to account for the unique

* Corresponding author.
E-mail address: wesley.cole@nrel.gov (W. Cole).

http://dx.doi.org/10.1016/j.apenergy.2016.02.004
0306-2619/

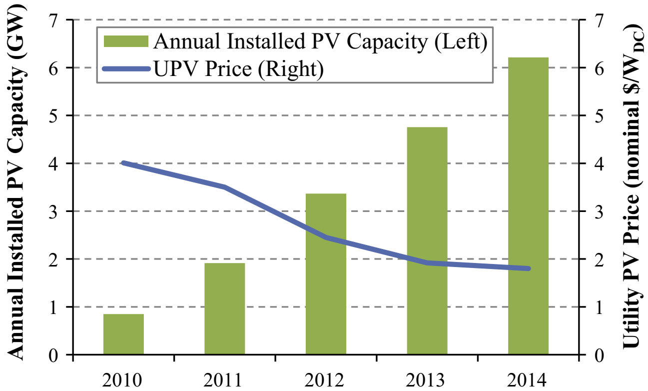

Fig. 1. Annual installed PV capacity (left axis) [1] and utility PV price (right axis) [8]. As PV prices have declined, annual installations have increased.

characteristics of variable renewable energy such as curtailment, variability, and effects on reserves. However the rapid uptake of utility-scale renewable energy has forced greater acknowledgement of their role in the bulk power system. High levels of variable renewable energy integration are now regularly considered in long-term projections and planning [9–14], and renewable energy impacts are getting additional attention to ensure they are more accurately represented [15]. However, many of these studies either ignore the contributions from demand-side sources, or treat them in a highly static fashion. Arnette [16] did consider a combined rooftop PV and bulk power system model, but the model was limited to a subset of the Eastern United States. In reality there are likely to be a number of important interaction effects, such as the contribution of demand-side generators to generation surplus, ramping requirements (e.g., the “duck curve”), and the effect of increased demand-side penetration on wholesale rates. These interaction effects will eventually impact retail rates, net metering, and other mechanisms for valuing demand-side generation. It is especially important to understand these interactions in high solar scenarios [17] because at high levels of PV penetration new PV generators tend to have decreasing value [18].[1]

This work aims to address this gap by bringing together two fundamentally different models to evaluate the interaction of rooftop PV deployment with the bulk power system. Different modeling frameworks are required due to the nature of the capacity expansion decisions. Utility-side investment decisions are often approximated as least-cost investment decisions, subject to meeting load, reliability requirements, transmission constraints, and environmental and policy regulations. Rooftop solar investment decisions, however, are typically independent of these considerations. Adoption decisions are still often cost-driven, but they typically do not consider the impacts of the rooftop system beyond one’s own home or office building. Also, costs for the rooftop systems are typically compared against retail rates, which are considerably higher than the wholesale rates used for utility-side decisions.

Thus, our primary contribution is to combine two capacity expansion models: one representing capacity expansion of the bulk power system and the other representing decision making of potential adopters of rooftop PV. Our goals are both to demonstrate a new method to improve the representation of PV in electric system capacity expansion modeling, and to illustrate how improved modeling methods can lead to insights into how rooftop PV deployment interacts with the evolution of the bulk power system.

[1] Lifecycle impacts are beyond the scope of this work. For more information on lifecycle assessments for photovoltaic electricity generation see [19,20].

This combined modeling framework allows us to consider impacts that, to our knowledge, have not yet been considered. For example, we assess the impacts of rooftop PV curtailment on the deployment of rooftop PV and consider the tradeoff of rooftop PV deployment with bulk power system evolution.

The focus of this work is on the long-term evolution, or capacity expansion, of the electricity system, and does not therefore focus on short-term or operation issues associated with high levels of PV deployment. There are technical challenges, such as limited inertia and voltage stability, associated with integrating high levels of PV, but those are discussed in other work (e.g., [17,21,22]).

2. Methods

In order to examine the interaction between rooftop PV deployment and the evolution of the bulk power electricity system, we linked two existing models: the Regional Energy Deployment System (ReEDS) model and dSolar model (formerly known as SolarDS). ReEDS is a utility-side model which makes decisions as a system-wide planner for power plants across the U.S. Because rooftop PV adoption is based on the decision of an individual or business, the ReEDS central planning framework is inappropriate for rooftop PV adoption. dSolar, on the other hand, was specifically designed to model consumer adoption of rooftop PV. Linking the two models together allows us to examine the interactions between rooftop PV deployment and the broader bulk power system.

Both ReEDS and dSolar have been used extensively for electricity sector modeling and analysis work. This section describes the two models and the method in which the models were linked. The scenarios used in the analysis are then presented and described.

2.1. ReEDS

We model the U.S. electricity sector using the ReEDS capacity expansion model [23,24]. ReEDS includes an optimization model that assesses the deployment and operation (including transmission) of the electricity sector of the contiguous United States from 2010 through 2050. The ReEDS model has frequently been used to investigate high renewable energy futures of the bulk power system [12,17,25–28]. ReEDS represents renewable energy resources through the use of 356 individual resource regions (for concentrating solar power [CSP] and wind resources) and 134 balancing areas (for utility PV, all other generation types, demand, and transmission) across the contiguous United States (see Fig. 2). ReEDS includes explicit representation of key issues related to renewable energy, such as variability and uncertainty in wind and solar output, transmission costs and constraints, and ancillary services requirements. ReEDS includes a full suite of conventional generating technologies, a reduced-form dispatch that reflects seasonal and diurnal load shapes, an aggregated transmission network, and dynamic natural gas supply curves. The major conventional thermal generating technologies in ReEDS include simple and combined cycle natural gas, several varieties of coal, oil/gas steam, and nuclear. In addition to conventional generators, ReEDS models geothermal, hydropower, biopower, wind, and solar energy resources. For solar energy technologies, ReEDS models central utility PV, distributed utility PV, and CSP with and without thermal energy storage. ReEDS does not explicitly model rooftop PV deployment; instead rooftop PV deployment is specified as an exogenous input to ReEDS. Electricity storage technologies in ReEDS include pumped-hydropower storage, compressed-air energy storage (CAES), and sodium sulfur batteries.

ReEDS includes statistical methods that endogenously assess the value of variable renewable energy generators. For each year,